Bioeconomic modeling of wetlands and waterfowl in Western Canada: Accounting for amenity values

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ABSTRACT

This study extends an original bioeconomic model of optimal duck harvest and wetland retention by bringing in amenity values related to the nonmarket (in situ) benefits of waterfowl plsi the ecosystem values of wetlands themselves. The model maximizes benefits to hunters as well as the amenity values of ducks and ecosystem benefits of wetlands, subject to the population dynamics. Results indicate that wetlands and duck harvests need to be increased relative to historical levels. Further, the socially optimal ratio of duck harvest to wetlands is larger than what has been observed historically. Including amenity values leads to a significant increase in the quantity of wetlands and duck harvests relative to models that focus only on hunting values.

Keywords: bioeconomic modelling; wetland protection; wildlife management; nonmarket values; Prairie pothole region

JEL Classification: Q57, C61, Q25

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1. INTRODUCTION

Climate change is expected to increase drought in Canada's grain belt, with projections suggesting that the 21st Century will be substantially drier than the previous one. A major casualty will be North America's duck factory – the pothole region of the southern Prairie Provinces. A drier climate will reduce the number of wetlands, which will have an adverse impact on agricultural ecosystems and the region's ability to produce waterfowl, as is clearly demonstrated by the high correlation between wetlands and breeding duck populations (Figure 1).

Wetland ecosystems are important not only for producing waterfowl, but also for the ecosystem services they provide. The latter include filtration of agricultural and other pollutants (thereby improving the quality of ground and some surface waters), provision of water for livestock and wildlife, visual and recreational amenities, greenhouse gas storage, and so on. Wetlands are also adversely impacted by policies that seek to mitigate climate change, particularly policies that subsidize production of corn, canola and other crops for biofuels, as their production increases the relative value of land in agriculture relative to wetlands.[1] Yet, waterfowl management models tend to focus on the hunting benefits of waterfowl, with wetlands often considered extraneous to the determination of hunting season length and bag limits – the tools of waterfowl management. Although decisions on optimal wetland retention are considered in some models, the value of the wetlands in the provision of other amenities is generally ignored.

[1] Crutzen et al. (2008) argue that the nitrogen oxides released from production of biofuels negate the CO_2-reducing benefits of replacing fossil fuels, and, particularly for canola, actually lead to an increase in relative warming.

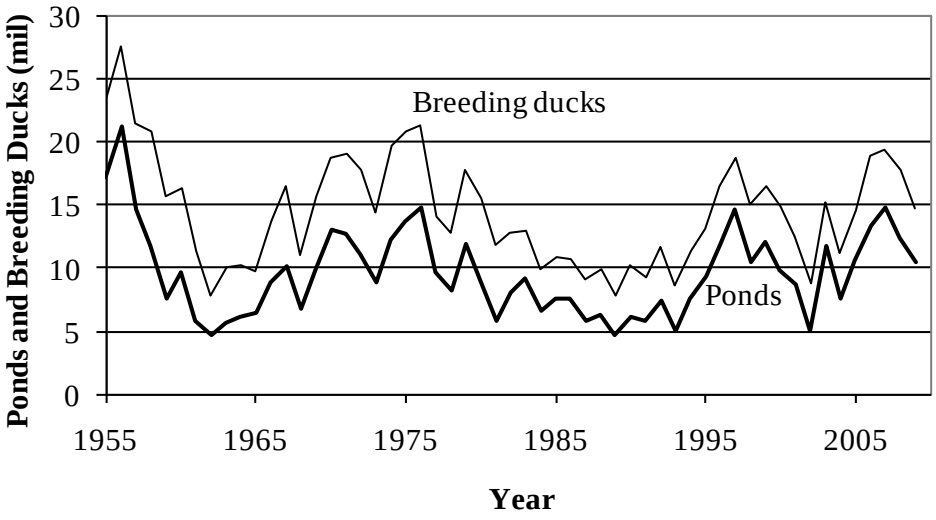

Figure 1: Relationship between Wetlands and Waterfowl in Canada's Grain Belt, 1955-2009

One of the earliest bioeconomic models of migratory waterfowl is due to Gardner Brown and Judd Hammack (Hammack and Brown 1974; Brown and Hammack 1973; Brown, Hammack and Tillman 1976). The model is discussed in more detail in the next section; here we note that the authors used a Beverton-Holt production function, estimates of duck survival rates and results from a U.S. survey of duck hunters to determine optimal levels of duck harvests and wetland protection. From these, they concluded that there were too few wetlands (by some 18% to 55%) in Canada's southern Prairie Provinces. Johnson et al. (1997) also focused on duck hunting, using a stochastic dynamic programming framework to address uncertainty related to random environmental and population variations and incomplete control over hunters' decisions. They find that, as wetlands in Canada's pothole region increase, the optimal management strategy is to have a more liberal hunting regime (longer hunting seasons and higher bag limits).

Recognizing that the majority of hunters are located in the United States (Figure 2) while the preponderance of breeding habitat is in Canada, the 1986 North American Waterfowl Management Plan (U.S. Department of Interior and Environment Canada 1986) was implemented as a mechanism by which the U.S. could compensate Canadian landowners for the positive externality that greater numbers of ponds in Canada provided U.S. hunters.[2] However, NAWMP was criticized for, among other things, simply offsetting the negative impacts of extant Canadian agricultural subsidies (van Kooten 1993a).

In addition to their consumptive use value to hunters, waterfowl also have non-consumptive use value (which might be negative for some who are adversely affected by goose droppings, for example), while wetlands have a variety of consumptive and non-consumptive use and non-use values (e.g., visual amenities) outside of their role in producing waterfowl. Therefore, management plans need to focus on the existence value of waterfowl and the amenity values of wetlands as much as or more so than hunting value. That is, a bioeconomic model of waterfowl and wetlands must simultaneously determine optimal strategies for managing waterfowl (setting harvest levels through decisions concerning season length and bag limits) and wetlands (determining how much wetland, or how many ponds, to retain).

[2] The focus of NAWMP was not only on provision of ponds. The program provided payments to farmers for providing dense nesting cover on lands that would otherwise be cropped, thereby enhancing the ability of waterfowl to reproduce. Ideally sites are to be fenced to keep out predators, but payments are usually inadequate. See van Kooten and Schmitz (1992) and van Kooten (1993b) for a more detailed discussion of these issues.

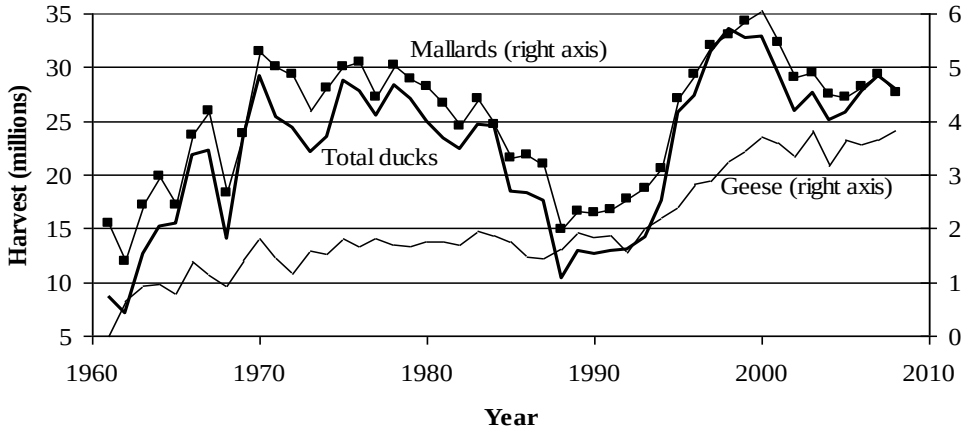

Figure 2a: U.S. Harvests of Ducks, Mallards and Geese, 1961-2008

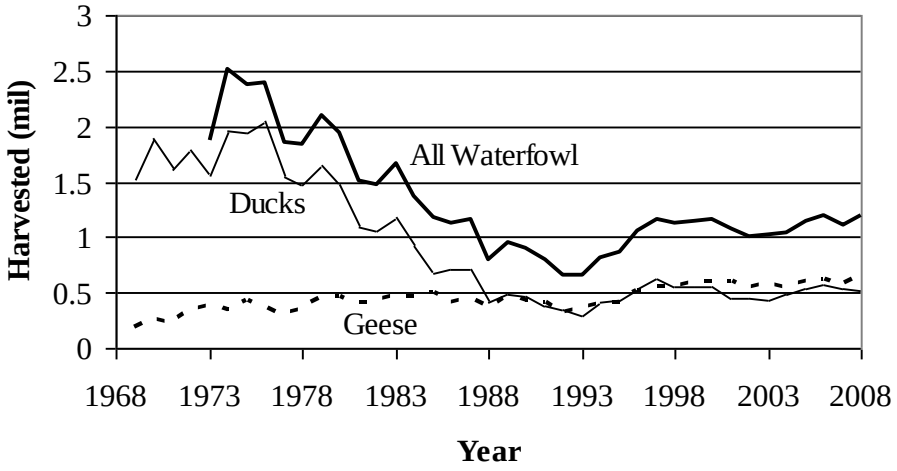

Figure 2b: Harvests of Ducks, Geese and All Waterfowl, Canada's Prairie Provinces, 1969-2008

Finally, waterfowl do not simply disappear when wetland area is reduced. They adapt by breeding in agricultural regions to the north, where (more plentiful) wetlands may become ice free earlier in the spring as a result of climate change, or they breed in the boreal forest zone of the Canadian Shield, although, in that case, productivity may be reduced. The point is that waterfowl management needs to take into account spatial as

well as dynamic aspects. At the heart of any spatial-dynamic model is the diffusion or dispersal process that governs the way waterfowl spread over space and create patterns (Wilen 2007). Patterns are generated by dynamic and spatial forces, of which climate is likely primary.

One can think about a hierarchy of bioeconomic models for wetland-waterfowl management and policy analysis. First come models that focus solely on the value of waterfowl to hunters, with wetlands considered exogenous (although their marginal value can be derived). Next come models that take into account amenity values of wetlands and the consumptive and non-consumptive values of waterfowl. Both classes of models could and perhaps should be characterized by uncertainty. Finally, models need to consider spatial aspects that affect the selection of breeding sites by returning birds. Although aspatial modeling can shed light on the impacts of climate change as the number of recruits (new ducks) is a function of wetland area (ponds) that is, in turn, dependent on climate factors, spatial factors should be included in future modeling efforts (Anderson and Titman 1992). In this paper, we only extend the hunting model to focus on the nonmarket values of wetlands and waterfowl, leaving to future research the impact of uncertainty and, importantly, climate change and spatial aspects.

The objectives in this study are, therefore, to (1) extend an original bioeconomic model by Brown and Hammack (1973), and Hammack and Brown (1974), hereafter H&B (1973, 1974), by bringing in amenity values related to the nonmarket (in situ) benefits of waterfowl and the ecosystem values of wetlands themselves; and (2) compare the outcomes of a model that considers only hunting values of waterfowl (the original H&B model) with those of our extended model. Opportunities and challenges of the

extended model will be discussed as will directions for future research.

2. BIOECONOMIC MODELING

Brown and Hammack (1973) were the first to use mathematical bioeconomic models (Clark 1976) to address wetland conservation. Such models optimize an objective subject to technical, biological, socioeconomic and political constraints. Approaches range from analytic to numeric, from deterministic to stochastic, from static to dynamic, from non-spatial to spatial (e.g. Dasgupta and Maler 2004; Miranda and Fackler 2002). Most models rely on computational methods that have been used extensively in agriculture (Howitt 2005; McCarl and Spreen 2004). H&B (1973, 1974) focused on duck hunting values, ignoring other waterfowl values and wetland benefits. We begin with a variant of the H&B model, and then expand the model to include the non-consumptive use value of waterfowl and, importantly, the in-situ value of wetlands.

Simple Waterfowl Harvest Model

H&B (1973) and Brown et al. (1976) specify a discrete bioeconomic optimal control model of duck hunting similar to that provided below.[3] The objective is to maximize benefits to hunters minus the costs of providing wetlands:

$$\sum_{t=1}^{T}\left[v(h_t, y_t, Z_t) - C(W_t)\right]\rho^t, \tag{1}$$

where $v(h_t, y_t, Z_t)$ is a function describing the benefits derived from duck hunting, which is a function of the number of ducks harvested (h), per capita income of duck hunters (y),

[3] Johnson et al. (1997) extend H&B's simple harvest management model to include uncertainty due to random environmental variation, incomplete control over harvests, and uncertainty about survival and reproduction. We also leave uncertainty to future research.

and such things as age, gender and outdoor experience that characterize duck hunters (Z); $C(W_t)$ is the cost of providing W amount of wetlands (measured by the number of ponds); and $\rho = 1/(1+r)$ is the discount factor with r the discount rate used by the hypothetical planner. The length of the planning horizon is T, and could possibly be infinite. In the H&B model, harvest levels and the number of ponds are decision variables.[4]

Ducks breed in the prairie pothole region in May and begin the fall flight south in September, which is also the start of hunting season. The fall flight consists of the fraction s_1 of May breeding ducks (D_t) that survive to September, plus offspring surviving to September. The latter is given by the recruitment function $g(D_t, W_t)$, where $\partial g/\partial D_t > 0$, $\partial^2 g/\partial D_t^2 \leq 0$, $\partial g/\partial W_t > 0$, $\partial^2 g/\partial W_t^2 \leq 0$. Equation (1) is maximized subject to the following bioeconomic constraints:

$$D_{t+1} = s_2 [s_1 D_t + g(D_t, W_t) - \pi h_t], \quad (2)$$

$$D_t, h_t, W_t \geq 0; \text{ and } D_0 > 0, W_0 > 0 \text{ given} \quad (3)$$

where D_{t+1} is the number of mature ducks returning to the prairie pothole breeding grounds in year $t+1$, s_1 is the fraction of May breeders surviving to September, s_2 is the fraction of mature ducks that are not killed by hunters and survive to return to the breeding grounds in year $t+1$, and $\pi > 1$ accounts for the loss of ducks that are killed or maimed by hunters but not collected or reported. Conditions (3) are non-negativity requirements and initial conditions regarding the numbers of ducks and ponds.

Applying Bellman's principle of optimality leads to the following recurrence relation known as Bellman's equation (Léonard and Van Long 1992, pp.174-176):

[4] H&B multiply $v(.)$ by the number of hunters, the control variable if bag limits and average take per hunter are constant. Here $v(.)$ is simply the benefit to all hunters.

$$V_t(h_t, D_t, W_t, \lambda_{t+1}) = \underset{h_t, W_t}{\text{Maximize}} \left\{ \left[v(h_t, y_t, Z_t) - C(W_t) \right] + \rho V_{t+1}(D_{t+1}) \right\} \quad (4)$$

where V_t is a value function and $\lambda_t = \partial V_t / \partial D_t$ is the shadow price of an additional duck. Equation (4) can be solved using backward recursion based on the assumption that the authority behaves optimally in the future so that the value at time $t+1$, V_{t+1}, is the best one can do.[5] The first-order conditions are found by first setting $\partial V_t / \partial h_t = 0$ and $\partial V_t / \partial W_t = 0$, and then differentiating both sides of (4) by the state variables D_t (recalling that D_{t+1} is a function of D_t).

Assuming an interior solution, the first-order conditions are:

$$\partial V_t / \partial h_t = \partial v / \partial h_t - \rho \, \lambda_{t+1} \, s_2 \, \pi = 0 \quad (5a)$$

$$\partial V_t / \partial W_t = -c + \rho \, \lambda_{t+1} \, s_2 \, \partial g / \partial W_t = 0 \quad (5b)$$

$$\partial V_t / \partial D_t = \lambda_t = \rho \, \lambda_{t+1} \, s_2 \, (s_1 + \partial g / \partial D_t) \quad (5c)$$

where $c = dC/dW_t$ is the cost of providing an additional pond.[6] Additionally, the state equation (2) must be satisfied; the sufficient conditions for a maximum are guaranteed by Bellman's optimality principle with $\lim_{t \to \infty} \lambda_t \rho^t D_t = 0$.[7] Equations (5a) and (5b) constitute a maximum principle, while equation (5c) is the co-state equation.

From maximum principle (5a), we find that $(1/\pi) \, \partial v / \partial h_t = \rho \, \lambda_{t+1} \, s_2$, which says that hunting should continue until the value of the marginal duck that is harvested

[5] The backward recursive approach of dynamic programming best lends itself to numerical solutions. In that case, T must be finite and the value $V_T(D_T)$ must be specified.
[6] The marginal cost of providing an additional pond need not be constant, but could be a function of the number of ponds, so that we would write $c(W_t) = dC/dW_t$.
[7] Notice also that functions $v(.)$ and $g(.)$ are taken to be non changing over time. Further, the last condition says that either it is optimal to drive the duck population to zero at some future time or the present shadow value of an additional duck is zero.

(adjusted for the fact that not all birds killed are recovered) equals the user cost of taking that bird (which equals its discounted shadow value adjusted for the fact that not all unharvested ducks survive to breed the following spring). Similarly, from maximum principle (5b), we find that $\rho\lambda_{t+1}\, s_2\, \partial g/\partial W_t = c$, which says that wetlands should be protected or created to the point at which the marginal value of an additional wetland in the production of ducks that return to the breeding ground next year equals the (marginal) cost of providing that wetland. The shadow value of next year's duck is adjusted by the discount factor ρ and the mortality risk. The shadow price of a pond, therefore, is given by its value in the production of future ducks. In the next subsection, we consider its amenity value in addition to its value in producing waterfowl.

Equation (5c) is simply an arbitrage condition. It requires that hunters take into account the value of allowing some ducks to escape to next year so they can breed to make more birds available in the future. Thus, the discounted future (shadow) value of allowing a duck to escape (adjusted for mortality and the marginal growth in duck population) must equal the current (shadow) value of harvesting that duck.

Substitute $\rho\, \lambda_{t+1}\, s_2$ from (5a) and from (5b) into (5c) to get the following expressions for the current shadow price of waterfowl:

$$\lambda_t = \frac{1}{\pi}\left(s_1 + \frac{\partial g}{\partial D_t}\right)\frac{\partial v_t}{\partial h_t} \text{ and} \tag{6a}$$

$$\lambda_t = \frac{c}{\dfrac{\partial g}{\partial W_t}}. \tag{6b}$$

Setting (6a) equal to (6b), and rearranging, gives a relationship similar to (5b), but one

that more clearly spells out the relationship between ponds and the value of waterfowl:

$$c = \frac{1}{\pi}\frac{\partial v}{\partial h_t}\left(s_1 + \frac{\partial g}{\partial D_t}\right)\frac{\partial g}{\partial W_t}. \tag{7}$$

The left-hand side of (7) is the (marginal) cost of providing an additional pond while the right-hand side is the value of the additional pond in the production of ducks for hunters.

A steady-state solution is found by letting $\lambda_{t+1}=\lambda_t$ and $D_{t+1}=D_t$, $\forall\, t$. We then find the following three steady-state conditions from equations (2), (5a), (5b) and (5c):

$$\frac{\partial v}{\partial h}\frac{\partial g}{\partial W} = c\pi, \tag{8a}$$

$$s_2\left(s_1 + \frac{\partial g}{\partial D}\right) - 1 = r, \text{ and} \tag{8b}$$

$$(1 - s_1 s_2)D = s_2\, g(D,W) - \pi\, h. \tag{8c}$$

Once functional forms and associated parameters are chosen for $C(.)$, $v(.)$ and $g(.)$, and the parameters s_1, s_2, r and π are determined, it is possible to find the optimal waterfowl population and optimal decisions concerning harvests and number of ponds that maximize the planner's wellbeing. (The three equations are used to solve for three unknowns.) However, wellbeing is based solely on benefits to hunters and excludes any other values of wetlands and waterfowl.

An Extended Bioeconomic Model of Waterfowl and Wetlands

We extend the original model by bringing in two types of amenity values – one is related to the nonmarket (non-consumptive use) benefits of waterfowl, while the other takes into account the amenity (ecosystem) values of wetlands themselves. Because we

include amenity values for both wetlands and waterfowl, the objective function (1) is modified as follows:

$$\sum_{t=1}^{T}\left[v(h_t, y_t, Z_t) + \alpha D_t + B(W_t) - C(W_t)\right]\rho^t, \tag{9}$$

where α is the amenity value of ducks, which could be positive for small numbers of ducks and negative for large numbers, say if large numbers lead to crop depredation. To keep things simple, we assume the amenity value is a positive constant. $B(W_t)$ is a wetlands ecosystem benefit function with $\partial^2 B/\partial W_t > 0$ and $\partial^2 B/\partial W_t^2 \leq 0$.

The revised Bellman equation becomes:

$$V_t(h_t, M_t, D_t, W_t, \lambda_{t+1}) = \underset{h_t, W_t}{\text{Maximize}}\left\{\left[v(h_t, y_t, Z_t) + \alpha D_t + B(W_t) - C(W_t)\right] + \rho V_{t+1}(D_{t+1})\right\}. \tag{10}$$

The first-order conditions are now:

$$\partial V_t/\partial h_t = \partial v/\partial h_t - \rho\, \lambda_{t+1}\, s_2\, \pi = 0 \tag{11a}$$

$$\partial V_t/\partial W_t = B'(W_t) - c + \rho\, \lambda_{t+1}\, s_2\, \partial g/\partial W_t = 0 \tag{11b}$$

$$\partial V_t/\partial D_t = \lambda_t = \alpha + \rho\, \lambda_{t+1}\, s_2\, (s_1 + \partial g/\partial D_t) \tag{11c}$$

The interpretation of equation (11a) is identical to that of (5a), while (11b) is similar to (5b), except for the additional term related to the marginal ecosystem benefits provided by wetlands, $B'(W_t)$. This is seen when we rearrange (11b) as follows: $c = B'(W_t) + \rho\, \lambda_{t+1}\, s_2\, \partial g/\partial W_t$. The left-hand side of this expression is the current cost of an additional pond, which is simply the cost of establishing or protecting it. The right-hand side is the marginal benefit of an additional pond, which consists of the current marginal amenity value of the pond, $B'(W_t)$, plus the shadow value of its marginal contribution to future

production of ducks discounted to the present.

The final condition (11c) is similar to (5c) except for the additional term α, which is the non-consumptive use value of a duck. Re-write (11c) as $\lambda_t - \alpha = \rho\lambda_{t+1}\, s_2(s_1+\partial g/\partial D_t)$. From the perspective of the planner, the shadow value of the marginal duck to hunters is reduced by α, indicating that the planner needs to take into account amenity values by raising the population of waterfowl over that in the previous model where ducks only had value to hunters. More ducks are allowed to escape to the next year than previously to satisfy both the need to make more birds available to hunters in the future and the non-consumptive use value ducks provide.

Again letting $\lambda_{t+1}=\lambda_t$ and $D_{t+1}=D_t$, $\forall\, t$, we can derive the modified steady-state conditions equivalent to those of equations (8):

$$B'(W)+\frac{1}{\pi}\frac{\partial v}{\partial h}\frac{\partial g}{\partial W}=c\,, \tag{12a}$$

$$\left(s_1 s_2+s_2\frac{\partial g}{\partial D}-1\right)+\frac{\pi s_2}{\partial v/\partial h}\alpha=r\,, \text{ and} \tag{12b}$$

$$(1-s_1 s_2)D = s_2\, g(D,\, W)-\pi\, h. \tag{12c}$$

Compared with results (8), those in (12) are modified to take into account the amenity values of in-situ wetlands and ducks, with only (12c) identical to (8c). Again, once parameters and functional forms have been determined, the three equations in (12) are used to solve for steady state levels of harvest, ponds and duck population.

3. WATERFOWL VALUATION AND THE EQUATIONS OF MOTION

An important component of bioeconomic modeling is the specification and

estimation of the objective function and the state equations (or equations of motion). Given lack of information about the demand function for duck hunting, we adapt the equation estimated by Brown and Hammack (H&B 1973) using H&B's (1974, p.29) mean values of the regressors, but adjusting mean hunters' incomes and expenditures on duck hunting by the U.S. CPI. The resulting valuation function is then $v(h) = 1.62\ h^{0.409}$. This function gives values of $2.15 for the harvest of two ducks and $3.37 for six ducks, while the marginal value of the sixth duck is $0.24; these values are clearly several orders of magnitude too small. H&B also multiplied this relation by the number of hunters.

In 2007, a total of 815,300 duck hunters in the Mississippi, Central and Pacific flyways spent an average of 7.2 days in the field and bagged 15.7 ducks; in 2008, 802,400 hunters harvested an average of 14.8 ducks and spent 7.1 days on the activity (Table 1). Using 1972-2008 data for Alberta, harvests averaged 12.8 ducks per hunter annually. Based on 20 studies, Loomis (2000) finds an average value of a wilderness recreation day to be $39.61 in 1996 US dollars, or $53.83 in 2008 after adjusting for inflation. Assuming duck hunters spend an average of 7 days in the field and harvest 14.5 birds, each bird is then worth approximately $26. Multiply this value by an average harvest of 12.3 million ducks over 2007 and 2008 in the Mississippi, Central and Pacific flyways gives a total benefit of $319.8 million. Assuming that the parameter value on harvest is 0.6, we calculate $v(h) = 70.947\ h^{0.6}$, with $v(h)$ and h measured in millions; if the original parameter is used, we find $v(h) = 114.580\ h^{0.409}$. We consider both functions as a sensitivity analysis.

Table 1: Duck Hunting and Harvest Data, United States, 2007 and 2008

Flyway	Year	Harvest	Hunters	Harvest per hunter	Days afield	Days per hunter
Mississippi	2007	6,719,700	474,400	14.2	3,479,100	7.3
	2008	6,522,900	466,400	14.0	3,410,000	7.3
Central	2007	2,666,000	193,400	13.8	1,127,400	5.8
	2008	2,086,700	178,300	11.7	946,100	5.3
Pacific	2007	3,441,000	147,500	23.3	1,269,900	8.6
	2008	3,300,600	157,700	20.9	1,303,300	8.3
U.S. Totals	2007	14,578,900	995,700	14.6	6,978,400	7.0
	2008	13,723,200	980,500	14.0	6,686,400	6.8

Source: http://www.fws.gov/migratorybirds/NewReportsPublications/HIP/hip.htm (as viewed January 7, 2010)

Woodward and Yong-Suhk (2001), and Brander, Florax and Vermaat (2006), used meta-regression analysis to determine the ecosystem service values of wetlands. The average wetland value in Brander et al. was $2800 per hectare, but the median value was only $150, indicating that the distribution of values is skewed with a long tail of high values. The median North American wetland value is somewhat higher than that in other locations, but much less than that for Europe, while wetlands of northern grain belt are likely to be less valuable than those elsewhere on the Continent. In Woodward and Song-Suhk, the average value of wetland services for benefit transfer purposes in Canada is $137 per acre, while the minimum value is $51 per acre. Furthermore, Cortus et al. (2010) estimate net public benefits of wetland retention in Saskatchewan; their 'best estimate' is $81.55 per hectare, while the low estimate is $39.62. In the current study, we use the low value of wetlands benefits from Cortus et al. (2010) as the base case but conduct sensitivity analysis using their best estimate.

In the above studies, benefits are measured in hectares or acres, and are not on a

pond basis. Cowardin, Shaffer and Arnold (1995) find that 78% of wetlands in the northern U.S. Great Plains cover 0.41 ha or less. Assuming an exponential distribution (which has only one parameter), we calculate the average pond to have an area of 0.27 ha.[8] Then the base case value is $10.69 per pond and the higher estimate for sensitivity purposes is $22.01 per pond, or constant marginal benefit of $10 and $22 per pond for convenience.

The net opportunity costs of protecting or restoring wetlands equals the reduction in the value of cultivated land or land in its best alternative use. In cases where flooding is common, or where wetlands are permanent, the cost might be zero. Net returns to agricultural land vary considerably from year to year, from one crop to another, and across the prairie pothole region. Cultivated areas in summer fallow and seeded acreage are provided in Figure 3, as are the number of May ponds, for the period 1955 to 2009. May ponds and the average subsidy paid per cultivated hectare are plotted in Figure 4. Clearly, the reduction in summer fallow area is the main driver for increases in seeded area, while ponds exhibit no discernable trend over the period 1955-2009. Ponds appear randomly distributed about a mean of about 3.4 million, likely depending more on climate factors than anything else. However, an inverse relationship between ponds and subsidies is discernable in Figure 4, particularly after about 1983 when Canadian agricultural subsidies rose rapidly in response to EU and U.S. agricultural programs.

[8] The cumulative probability function is: Prob($x<X$) = $1 - e^{-3.693\,x}$. H&B (1974, p.69) indicate that the average size of a pond in the Prairie pothole region was determined to be 0.85 acres or 0.34 hectares.

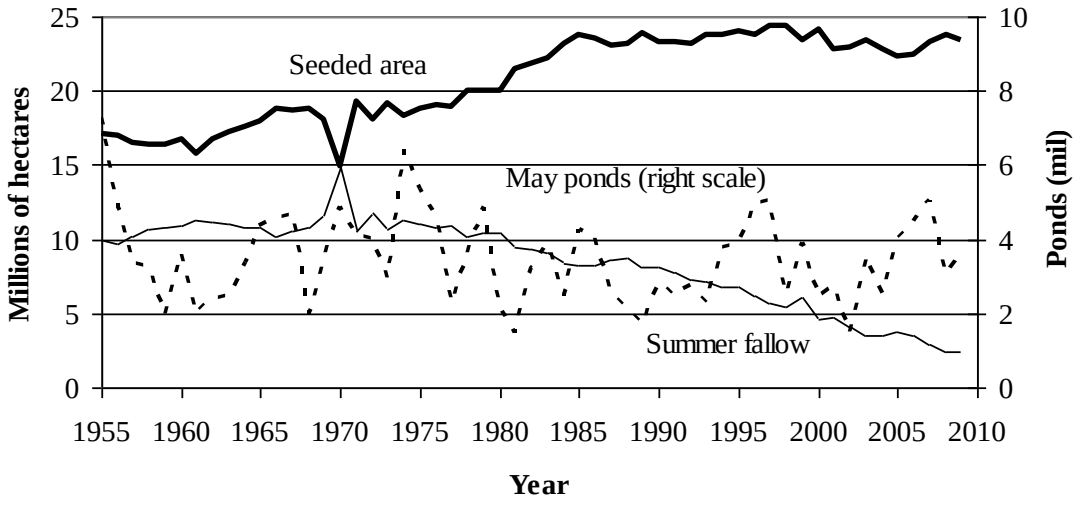

Figure 3: May Ponds, Seeded Area and Summer Fallow, Prairie Provinces, 1955-2009

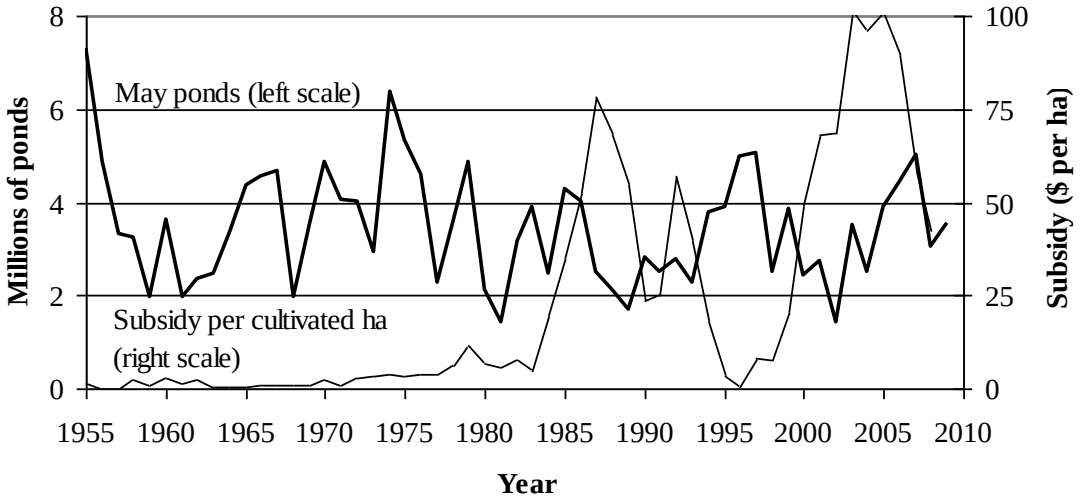

Figure 4: May Ponds (1955-2009) and Subsidy per Cultivated Hectare (1955-2008), Prairie Provinces

Hansen (2009) provides information on the costs of restoring wetlands based on the USDA's Wetlands Restoration Program. For the prairie pothole area, average restoration costs rose from $545 per acre ($1,346 per ha) for the 25th percentile to $1,160 ($3,132/ha) for the 50th percentile, and $1,953 ($4,824/ha) for the 75th percentile (in 2007

US dollars). This translates into costs of about $360, $840 and $1,300 per pond for the 25th, 50th and 75th percentiles, respectively. It is important, however, to recognize that payments under this Program are for wetlands over and above ones that might be considered 'permanent' as landowners have never made the effort to convert them to cropland. The least number of ponds during the period 1955-2009 was 1.439 million in 2002 when precipitation was low.[9] The cost to the authority of providing this minimum level of wetlands is likely close to zero; indeed, costs are likely not incurred until wetlands rise above about 2.0 million and then only if there are significant subsidies to landowners (see Figure 4). With increased emphasis on biofuels, it is likely that conditions similar to those occurring in 1987 and 2003-2005 can be expected to prevail in the future. For simplicity, we assume that the marginal cost of protecting a pond is constant. Given that the cost is zero for the first 2 million ponds, the values in Hansen are likely far too high. Therefore, we employ a range between $70 and $120 for the marginal cost per pond, and use the low value ($360) provided in Hansen as sensitivity analysis.

B&H (1973, 1974) and Brown et al. (1976) use two functional forms for the waterfowl production function – a double-logarithmic form (or Cobb-Douglas) and a Beverton-Holt production function. The respective functional forms are:

$$g(D_t, W_t) = AD_t^{\varphi_1} W_t^{\varphi_2} \text{ and} \tag{13a}$$

$$g(D_t, W_t) = \left(\frac{d_0}{D_t} + \frac{1}{d_1 W_t^{d_2}} \right)^{-1}. \tag{13b}$$

[9] The maximum number of May ponds was 7.302 million, but this occurred in 1955 and might be considered an outlier. Ignoring this value, the maximum of 6.390 million occurred in 1974.

As the number of breeding ducks grows to infinity, the number of offspring grows indefinitely large in the case of the Cobb-Douglas production function, but is bounded by the available habitat (the ecosystem carrying capacity) in the case of the Beverton-Holt model – the limit approaches $d_1 W_t^{d_2}$ asymptotically. We also examine a standard logistic growth function (which is now commonly used in bioeconomic models):

$$g(D_t, W_t) = rD_t\left(1 - \frac{D_t}{gW_t^b}\right) \tag{13c}$$

where gW_t^b is the carrying capacity of the prairie pothole ecosystem.

We have data on breeding ducks and immature offspring, and on wetlands (May pond counts), for the Prairie Pothole region of southern Alberta, Saskatchewan and Manitoba (strata 26 through 40) over the period 1955 to 2009. We also have data on July ponds for the period 1955-2003, U.S. duck harvests for the Central flyway for the period 1961-2008, and Canadian harvests of ducks for the period 1969-2008. We use this data to estimate the relationships 13(c) and 13(a). Similar to H&B, we find that May ponds provide a better statistical fit than July ponds, so we present only the regression results with May ponds.

The regression results are as follows:[10]

$$g(D_t, W_t) = \underset{(0.32)}{0.880} \quad \underset{(4.73)}{D^{0.924}} \quad \underset{(3.59)}{W^{0.608}}, \; R^2 = 0.6715, \text{ se} = 0.3379, \text{ n}=54 \tag{14a}$$

[10] The t-statistics are in parenthesis below the expression in which the estimated coefficient is found and are based on Newey-West HAC standard errors.

$$g(D_t, W_t) = \underset{(4.88)}{\left(\frac{0.430}{D} + \frac{1}{\underset{(1.79)}{5.668}W^{\underset{(2.85)}{2.024}}}\right)^{-1}}, \quad R^2 = 0.6715,\ se = 6.2645,\ n=52 \tag{14b}$$

$$g(D_t, W_t) = \underset{(8.56)}{2.18}D\left(1 - \frac{D}{\underset{(3.24)}{8.48}W^{\underset{(3.52)}{1.50}}}\right), \quad R^2 = 0.677,\ se = 6.3423,\ n=52 \tag{14c}$$

Unlike H&B's (1974, p.49) regression, our Cobb-Douglas production function (14a) does not exhibit constant returns to scale as the sum of the estimated coefficients exceeds 1.0 (0.924+0.608=1.532), indicating increasing returns to scale production. If we apply the estimated parameters of Cobb-Douglas equation 14(a), we find that increases in the costs of restoring wetlands are offset in the steady state by unbounded increases in optimal breeding populations, an unrealistic result. For the estimated parameters of the Beverton-Holt model in (14b), the dynamic model turns out to be highly unstable, which is not unusual as noted by van Kooten and Bulte (2000, p.184). Consequently, we rely on the estimated logistics growth function (14c) in the numerical analysis.

Finally, we employ H&B's (1974, p.50) values for intra-year survival rates for the period between breeding in May and the start of hunting season in September (s_1) and the period after hunting season until breeding begins (s_2). Brown et al. (1976) assume 5% of duck kills are not reported, and we use this factor to account for underreporting of bird kills by hunters. Loomis and White (1996) report non-consumptive use values for several endangered bird species, which are quite large for some species such as Whooping Crane. Ducks and geese tend to be plentiful, so their value to bird watchers and other viewers tends to be smaller. Therefore, we use a very low value and a value equal to the lowest value of an endangered species as reported by Loomis and White.

4. NUMERICAL SIMULATION RESULTS

We determine the steady-state solutions by solving the system of equations (8) in the case where only hunter values are considered and the system (12) if wetlands are considered to have value. A summary of the functions and parameter values used in the simulations is provided in Table 2. Table 3 presents steady state values of ducks, harvests and wetlands. These results correspond to the base case values provided in Table 2.

Optimal values for ducks and ponds in Table 3 are calibrated to the Canadian prairie pothole region, because the production function was estimated using prairie pothole duck and pond data. The harvest is the combined kill in the U.S. Mississippi, Central and Pacific regions, while the duck valuation function was based on a survey conducted in the Pacific region. In order to calibrate the duck valuation function to other flyways, it is assumed that people's preferences are similar across regions.

From Table 3, several patterns are discernable when the costs of wetlands restoration are varied. First, using Hansen's (2009) lowest estimated cost of wetland restoration, $360 per pond, the level of ponds, ducks and harvests is extremely small relative to historical levels. Further, using a cost of $12-$17 per pond, such as in Brown and Hammack (1973), it is optimal to restore an extremely high number of ponds, with consequently high steady-state levels of ducks and harvests. For the current model, we use a range of costs for wetland restoration between $70 and $115 per pond. As discussed above, the costs estimated in Hansen (2009) are only to be incurred after the first two million ponds or so, in which case the average cost per pond would be much lower.

Table 2: Model Sensitivity Functions and Parameters used in Simulations

Item	Base Case Value	Sensitivity Value
Marginal hunter benefit function	$\partial v/\partial h = 46.863\ h^{-0.6}$	$\partial v/\partial h = 42.568\ h^{-0.4}$
Marginal product of wetlands in duck production	$\partial g/\partial W = 0.385 D^2 W^{-2.5}$	$\partial g/\partial W = 0.535\ D^{0.924}\ W^{-0.392}$
Marginal product of breeding ducks	$\partial g/\partial D = 2.18 - 0.514 D W^{-1.5}$	$\partial g/\partial D = 0.813\ D^{-0.076}\ W^{0.608}$
Intra-year duck survival rates	$s_1 = 0.95$ $s_2 = 0.80$	$s_1 = 0.95$ $s_2 = 0.85$
Marginal cost of protecting wetlands	$c = C'(W)$ = \$70, 90, 115, 360	$c = C'(W)$ = \$70, 90, 115, 360
Marginal amenity value of wetlands	$B'(W)$ = \$10.00	$B'(W)$ = \$20
Marginal non-hunting value of a duck	α = \$1	α = \$2
Adjustment for underreporting of kills	π =1.05	π =1.05

Table 3: Historic and Steady State Values of Ponds, Ducks and Harvests, Various Costs of Wetlands Restoration (millions)

Item	Ponds (W)	Ducks (D)	Harvests (h)
Historic [a]	3.5	13.5	14.1
Cost=\$70/pond			
Hunter value	3.5	22.7	17.2
Amenity value	15.0	256.0	1q55.0
Cost=\$90/pond			
Hunter value	1.9	8.8	6.7
Amenity value	3.8	28.0	19.0
Cost=\$115/pond			
Hunter value	1.0	3.5	2.7
Amenity value	1.6	7.2	5.3
Cost=\$360/pond			
Hunter value	0.05	0.04	0.03
Amenity value	0.09	0.10	0.07

[a] Source: Ponds and ducks are for Canada's prairie region and based on the average of 1955-2008 data from the U.S. Fish and Wildlife Service (http://mbdcapps.fws.gov/); harvest is the average of total 2007-2008 U.S. harvest (www.fws.gov/migratorybirds/NewReportsPublications/HIP/hip.htm).

Second, for a basic model similar to that of Brown and Hammack (1973) but with a cost of $90 per pond, optimal wetlands, ducks and harvests are projected to be 1.9, 8.8 and 6.7 million, respectively. These values are all smaller than historical values, a result that is contrary to H&B (1973). However, as one decreases the cost of ponds, the optimal value of all of these variables increases significantly.

Third, a key result from Table 3 is that the addition of wetland amenity values and in-situ values of ducks will lead to increased wetlands, ducks and harvests. Clearly, increasing the marginal benefit of a pond should increase the number of ponds, although it also leads to an increase in ducks and harvests as a result of greater breeding habitat. Further, increasing α – the amenity value of a duck – will decrease the shadow value of the marginal duck to hunters, indicating that the planner needs to raise the population of waterfowl over that in the previous model where ducks only had value to hunters. The increase in ducks will also impact ponds and harvests. When the cost of wetlands restoration is $90/pond, optimal ponds, ducks and harvests are 3.76, 28 and 19 million, respectively. These values are much higher for the same restoration cost levels than those provided in the model that uses only hunter values, and are also higher than historical levels.

Finally, in addition to the actual values obtained in Table 3, ratios of ducks per pond and harvests per pond are also easily obtained by solving the basic model using only hunter values. These ratios are similar when we add amenity values, although more complicated expressions result. For May pond data, the historical levels are 3.85 and 4.02 ducks and harvests per pond, respectively. In the current model, the optimal level of

ducks and harvests to ponds is $3.5W^{1.5}$ and $2.65W^{1.5}$, respectively. This can be verified using the values in Table 3. Using the average May pond count for the period 1955 to 2008 (3.5 million), the model projects optimal duck numbers at 22.9 per pond and harvests of 17.35 per pond. Thus, historic levels of both waterfowl and harvests are too low from a social planner's perspective for the given the number of wetlands. When amenity values are included, the ratio of ducks and harvests to ponds is larger than in the original model, despite the increased value of ponds. This is due to the fact that the amenity values of ducks increases the optimal number of ducks (and therefore harvests), while the greater number of wetlands will further increase ducks and harvests.

In addition to being sensitive to different levels of wetlands restoration costs, the results are quite sensitive to functional forms and parameter values. Both an increase in the marginal nonmarket value of ponds and the amenity value of ducks will raise optimal wetlands, ducks and harvests. This is seen in Table 4, which compares values in Table 3 to those using $B'(W)$ values of \$20 and α values of \$2 per duck, for wetlands restoration costs of \$90 and \$115 per pond. Note that, for the parameters chosen here, the ratios of ducks and ponds increases as we increase the marginal benefit of ponds and the amenity value of ducks.

Furthermore, different specifications of the waterfowl production and duck valuation functions will impact the results. Using a Cobb-Douglas form, we get increasing returns to scale (14a), as discussed above. This will result in significantly higher duck and harvest levels than could realistically occur and results are not included here. Even changing the parameters on the current duck valuation function, such that $\partial v/\partial h = 42.568\, h^{-0.4}$, will result in values of wetlands, ducks and harvests than are

significantly higher than those in Table 3. The impact of functional form can be seen by comparing the results in Table 3 with those of Table 5, which includes different functional forms for production and in-situ duck values, for wetlands restoration costs of $90 and $115 per pond.

Table 4: Sensitivity of Ponds and Ducks to Changes in to Amenity Values, Millions

Item	Ponds (W)	Ducks (D)	Harvests (h)
Historic values	3.5	13.5	14.1
		Cost=$90/pond	
Hunter value	1.9	8.8	6.7
Amenity values			
$B'(W)=10$, $\alpha=1$	3.8	28.0	19.0
$B'(W)=20$, $\alpha=1$	6.6	66.8	44.9
$B'(W)=10$, $\alpha=2$	7.0	78.9	48.5
		Cost=$115/pond	
Hunter value	1.0	3.5	2.7
Amenity values			
$B'(W)=10$, $\alpha=1$	1.6	7.2	5.3
$B'(W)=20$, $\alpha=1$	2.1	11.5	8.3
$B'(W)=10$, $\alpha=2$	2.0	10.8	7.5

Results are clearly very sensitive to functional form and parameter values; yet, there are some key policy conclusions, the second and third of which reinforce the earlier findings by H&B (1973, 1974). First, from the social planner's point of view, the optimal management of waterfowl is such that wetlands, ducks and harvests should all be higher than historically observed levels. Second, it is important to add amenity values in the current model; including amenity values significantly increases the level of wetlands, ducks and harvests relative to a model that does not include these values. Third, based on

the results in this model, the level of ducks and harvest relative to the level of May ponds should be higher than historically observed levels.

Table 5: Sensitivity to Duck Valuation Function

Item	Ponds (W)	Ducks (D)	Harvests (h)
		(millions)	
Historic Value	3.5	13.5	14.1
Cost = \$90/pond; $\partial v/\partial h = 46.863\ h^{-0.6}$			
Hunter Value	1.9	8.8	6.7
Amenity Values	3.8	28.0	19.0
Cost = \$90/pond; $\partial v/\partial h = 42.568\ h^{-0.4}$			
Hunters Value	32.0	657.0	497.0
Amenity Values	8.9	81.0	69.0
Cost = \$115/pond; $\partial v/\partial h = 46.863\ h^{-0.6}$			
Hunters Value	1.0	3.5	2.7
Amenity Values	1.6	7.2	5.3
Cost = \$115/pond; $\partial v/\partial h = 42.568\ h^{-0.4}$			
Hunters Value	2.8	16.8	12.6
Amenity Values	10.6	122.0	93.0

5. CONCLUDING OBSERVATIONS

Gardner Brown and Judd Hammack were the first to employ bioeconomic modeling in a wildlife context, demonstrating that, on the basis of duck hunting values alone, the socially optimal level of wetlands protection was below the existing level. In coming to this conclusion, these researchers ignored the ecosystem service and other amenity benefits associated with wetlands as well as the benefits people get from viewing waterfowl. In this study, we sought first to duplicate their results and then extend their analysis to include nonmarket in-situ values of waterfowl and wetlands. While we could duplicate their results for the parameters they had estimated, we found that estimates

using updated data led to a Cobb-Douglas production function with increasing returns to scale in wetlands and breeding ducks, leading to an unrealistic result. For the Beverton-Holt model parameters of equation (14b), the dynamic model turned out to be highly unstable. For these reasons, we used a logistic production function that is commonly used in bioeconomic wildlife models.

When the model based only on hunting values was expanded to include the non-consumptive use value of waterfowl and the ecosystem service and amenity values of wetlands, the optimal steady-state levels of ducks and wetlands to retain increased significantly. Thus, Brown and Hammack's (1973) original conclusion was reinforced – the numbers of wetlands protected in the Canadian prairie pothole region is less than what is socially optimal.

In our analysis, we relied exclusively on sensitivity analysis to address randomness, recognizing that this does not lead the authority to take explicit account of such uncertainty in making decisions. That is, optimal management strategies obtained from sensitivity analysis are not necessarily optimal from the perspective of a planner who considers randomness in the decision calculus. Future research needs to take uncertainty into explicit account, including uncertainty related to future climate change. In addition to uncertainty, it is important that future research also take into account spatial aspects.

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